EMERGING TECHNOLOGIES IN UNDERWATER MUNITIONS MAPPING

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Abstract: *For centuries, oceans, lakes and rivers throughout the world have been the repository of expended and discarded munitions, through various activities such as military engagement, weapons testing and training, accidents, and by dumping. With population and economic activity growing adjacent to coastal and inland waters, many nations are investing in and developing new technologies to map these areas to determine the extent and threat of underwater munitions. The obvious physical challenge of operating underwater is compounded by light-attenuating turbidity, lack of positional accuracy due to the absorption of RF signals, the abundance of man-made objects and natural features that confuse sensors (i.e. clutter), and the common situation that objects deposited in sedimentary environments bury making them opaque to many sensing modalities. As expected, different environments lend themselves to different sensing modalities, and may require different combinations of optic, acoustic, magnetic, electromagnetic induction, and chemical sensors. This paper reviews conventional underwater sensing technologies that have been used to date with various levels of success, describes the challenges posed by many common environments encountered, and discusses emerging advances in underwater sensors, platforms, and automation predicted to increase the efficiency of munitions remediation in many areas, and make munitions detection and classification possible for the first time in some of the more challenging environments. These advances are being evaluated and realized at an accelerated pace due to a number of international collaborations in munitions response described herein.*

Keywords: *Dumped Ammunition, Unexploded Ordnance, UXO, Munitions Response, Side Scan Sonar, Synthetic Aperture Sonar, Magnetometer, Electromagnetic Induction*

1. INTRODUCTION

For centuries, oceans, lakes and rivers throughout the world have been the repository of expended and discarded munitions, through various activities such as military engagement, weapons testing and training, accidents, and by dumping. Different types of ammunition used in military operations during the two World Wars in Europe are encountered periodically in rivers, bays, and at sea. As examples: in 2005, three fishermen lost their lives in the North Sea when a WWII bomb exploded on their vessel after it was hauled aboard in their fishing nets [1]. In 2015, a family on a beach in Wales played on top of what appeared to be a fouled buoy, but which turned out to be a U.S. WWII moored mine [2]. The size distribution of underwater expended or unexploded ordnance (UXO) is much broader than the given examples suggest, ranging from single rifle cartridges and artillery shells, to sea mines, 2000 lbs bombs, V1 missiles or missile heads, and torpedoes or torpedo heads.

In the North Sea and the Baltic Sea approximately 700,000 mines were laid during the two World Wars [3], many of these unrecovered and regularly found to this day. Following these conflicts, millions of tons of munitions ranging from conventional to phosphorus incendiary devices to chemical munitions containing mustard gas and other substances, were dumped by many nations in an oceanic arc spanning from Spain to Norway. Underwater munitions disposal was stopped in 1972 when international agreements were reached to regulate the dumping of material at sea [1,4]. In the U.S. many active and former military installations, some dating as far back as the 18th century, have artillery/bombing/training areas that include adjacent water environments and coastal ocean areas. Over the years, weapons testing, disposal and accidents have generated munitions contamination in the coastal and inland waters throughout the country. The U.S. Army Corps of Engineers has identified more than 400 underwater formerly used defense sites potentially contaminated with munitions, and the U.S. Navy Munitions Response Program manages more than 50 closed and active sites potentially contaminated with munitions [5].

Three acknowledged dangers caused by expended, lost or discarded munitions include: direct physical contact with either chemical or conventional munitions resulting in threats to human health; contamination of marine organisms and the environment with the potential for concentration of toxic contaminants up the food chain; and spontaneous explosions which can be directly life threatening and spread munitions material [6]. Direct physical contact or disturbance of munitions can occur through activities such as fishing, laying cables and pipelines, construction, dredging, and diving, with the former accounting for more than half of encounters. The highest density of encounters for European waters has been reported in the southern North Sea between the United Kingdom and the Netherlands [1].

Until about 2010, offshore UXO detection and removal operations were carried out on a small scale; however, since then, European and U.S. initiatives in mapping and remediating UXO contamination have grown significantly [3,4,7-10]. This is due largely to population and economic activity growing adjacent to coastal areas, thus increasing utilization of the maritime environment for food (fisheries), energy production (offshore oil and gas, wind farms, tidal power), commerce (harbour construction and extension, seabed pipelines and telecommunication cables), and recreation.

Tools for terrestrial UXO detection have been developed and standardized over many years and rely primarily on passive magnetic systems that measure a ferrous object's disturbance of the earth's magnetic field and pulsed electromagnetic induction (EMI) systems that measure induced eddy currents in objects. UXO surveys in water bodies have until recently been primarily conducted by using geophysical survey gear such as magnetometers, acoustic imaging systems that include side scan sonars (SSS) and multi-beam echosounders (MBE), and underwater cameras for object identification.

2. CHALLENGES & INNOVATION

There are numerous challenges to UXO mapping, first and foremost being that the location of many areas associated with military engagement, testing or dumping were not well documented, if at all, thus requiring the need for precision sensors with wide area coverage rates. Conditions that can challenge sensors include the fact that unexploded ordnance: has a broad size distribution with diverse composition; can be encrusted, fragmented and buried in the sediment; and can reside in complex underwater environments. Bottom types can vary from mud to sand to rock, the water-sediment interface can vary from smooth to rough to rippled modulated by the impacts of fishing activity and bioturbation, and platform-challenging hydrodynamic conditions such as high currents and shallow beach heads are common.

Passive magnetic arrays towed from surface vessels or integrated onto underwater vehicles have been shown to detect larger UXO on top of or buried in the sediment, and when combined with accurate positioning, can provide seafloor magnetic contour maps– with some systems demonstrating the capability of providing accurate data inversions yielding target parameters, including location, size, and depth. The biggest issues are short stand-off distances (1-3 m from the seafloor for magnetics and closer for EMI), accurate navigation, and electromagnetic interference emanating from the platform. High-frequency commercial off-the-shelf (COTS) side scan, multi-beam and forward-looking sonars are capable of creating modest-range (tens of meters) high-resolution images of the seabed and UXO lying thereon. These systems offer higher area coverage rates than magnetic sensors; however, they are range-limited due to the sonar's radial beam pattern, and unable to detect buried objects in dense substrates due to short-wavelength acoustic attenuation. With the exception of certain tropical and stillwater environments, COTS optical systems such as underwater cameras have shown limited utility in UXO mapping due to light attenuating turbidity, and to date have been used primarily for close-range target identification.

An emerging generation of high-end underwater sensors and platforms, many with continuously reducing price points, are beginning to impact UXO mapping applications. These underwater mapping systems can be airborne, shipborne, towfish mounted, or deployed on unmanned tethered or autonomous surface and undersea vehicles; and to date each of these platform types has been employed or proposed for undersea UXO mapping. Each platform type has its respective pros and cons depending on targets expected, the environment encountered, and the budget/manpower of the surveyor. For example, a shallow clear-water environment with only exposed (i.e. non-buried) munitions may lend itself to a high-speed airborne survey with an optical sensor. However, a coarse sandy environment with predominantly buried artefacts will likely require the use of short-standoff sensors mounted on an underwater platform. Some water depths will lend themselves to shipborne sensors, whereas knee-deep water depths, typical of a recreational beach exhibiting sand mobility, will likely require a small manned or unmanned surface craft or crawler employing magnetics. Over the coming years the choice of platform(s), along with sensors, for UXO mapping will require tradeoff studies on concepts of employment that account for the conditions described above, along with anticipated manning requirements and anticipated price reduction of select technologies.

Associated with the choice of platform will be the ability to precisely navigate and to localize sensed munitions. While sensors mounted on airborne and surface craft have the benefit of GPS positioning, underwater sensors operating in this RF-attenuating GPS-denied environment will require navigation aids such as: inertial navigation systems (INS) which may be aided by Doppler velocity log (DVL) sonars and Kalman filter state estimation algorithms, such as found on many lightweight autonomous undersea vehicles (AUV); Ultrashort Baseline (USBL) underwater acoustic positioning systems that aid in determining the position of a towfish relative to the survey craft in order to exploit shipborne GPS; or the use of markers or features on the bottom for positional referencing via sensor data.

Emerging Sensors for Underwater UXO Mapping

Despite inherent range restrictions, total-field magnetometers and gradiometers continue to show utility and technological advances in underwater applications; e.g., AUV-deployment of high-performance gradiometers using a laser for optical pumping of helium-4 or cesium gas to increase sensitivity [8], and towfish-mounted superconducting quantum interference device (SQUID) based gradiometers [9]. Since the total magnetic field of an object drops approximately with the third order in range, a detectable magnetic anomaly is roughly reduced by a factor of 8 when doubling the distance between an object and a magnetic detector. Thus the total magnetic anomaly for a 250 lbs bomb (~ 110 kg) will decrease from 800 nT at a distance of 1 m, to 100 nT at a distance of 2 m, to 12 nT at a distance of 4 m, etc… [3]. This decay helps to illustrate the tradeoffs in platform type. Executing a dense survey grid with the required lane separation of several meters is a task well suited to an AUV; however, the magnetic influence of the propulsion motor and other vehicle components can present background noise that exceeds the detection floor of the sensor. Typically a towfish is magnetically quieter than an AUV for accommodating sensitive magnetic sensors [11]; however, active motion-control surfaces may be required to achieve the trajectory requirements of low altitude and tight lane spacing. The primary advantages of these sensors are that they detect exposed as well as buried objects, and that they are normally not significantly influenced by sediment properties of the seafloor. However, due to the measured small magnetic anomalies caused by single pieces of ammunition and a varying signal background caused by the seafloor, complications can arise in munitions detection [11]. It should be noted that even WWII ammunition exists that was manufactured with aluminum or other non-ferromagnetic materials which cannot be detected by these sensors. To identify these non-ferrous materials it is expected that EMI systems adapted to work in these environments will play a role.

The synthetic aperture sonar (SAS) is one of the newest, innovative developments in the field of acoustic seabed imaging. By coherent processing of data from a series of consecutive pings a significantly longer receive aperture is synthesized in the direction of travel. When synthetic aperture techniques are applied at sufficiently low acoustic frequencies, where sound absorption in the ocean medium is reduced, a modest-sized system can generate imagery with a constant lateral resolution comparable to that of higher frequency sonar systems, but with a longer range potential [12]. Hence, the lateral resolution is often improved by an order of magnitude or more for SAS systems compared to conventional SSS, with typical resolutions of 2-4 cm along and across track. This significantly higher resolution results in enhanced object classification capability at higher area coverage rates. SAS systems have seen increasing use for UXO mapping throughout the decade [5,8-11]. Figure 1 gives as an example a SAS and a MBE image from a dumping site in German waters. Shown is a cluster of about 70 moored mines from WWII laying on the seabed. In the left SAS image the individual oval-round shapes of each mine is clearly visible due to the high resolution of 2-4 cm. This is not the case in the right MBE image due to the lower resolution of about 25 cm, but the structure of the mine cluster can be clearly identified.

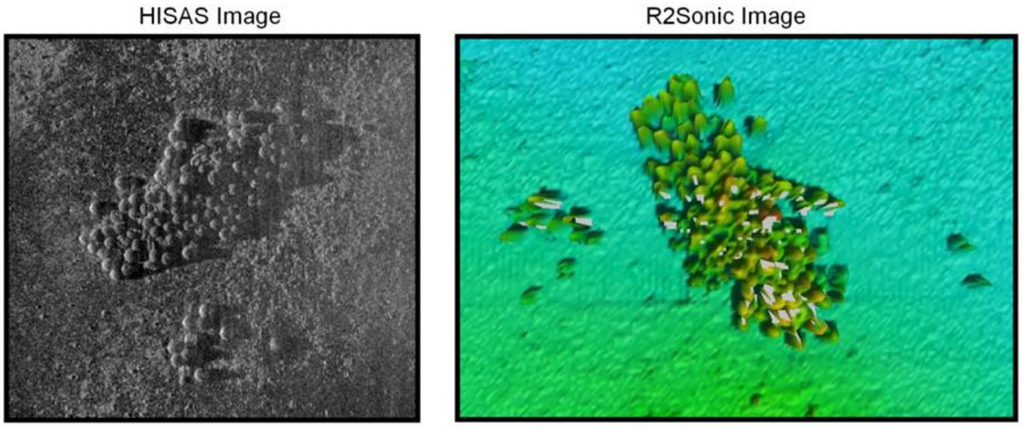

Fig.1: SAS (left) and MBE (right) images of approximately 70 moored mines from a dumping site in German waters.

Recently, circular synthetic aperture sonar (CSAS) techniques for UXO identification have been developed [8,9,13]. CSAS involves circling the sonar about a detected object to create a fused, very high resolution image from all aspects. Although falling short of optical imagery, CSAS imaging far exceeds the quality obtained with conventional sonars. This imaging modality has been successfully used to confirm the identity of UXO-like objects as in Fig. 2, and has been key to determining when and where to employ divers for remediation purposes.

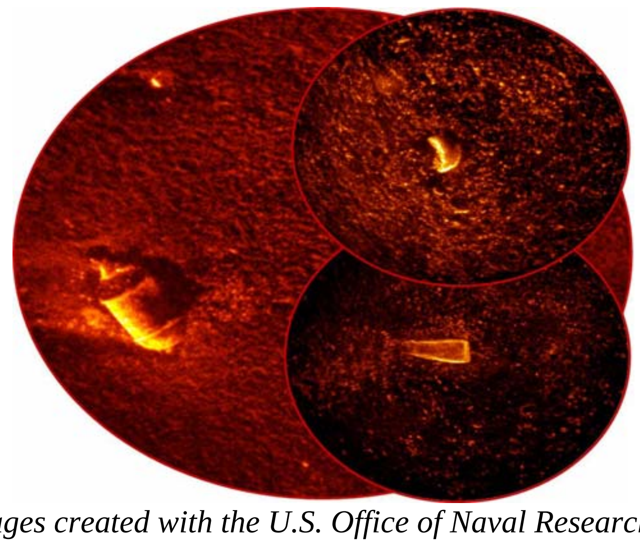

Fig.2: CSAS images created with the U.S. Office of Naval Research Small Synthetic Aperture Minehunter (SSAM) sonar, enabling identification of WWII-era mine remnants (left), fractured sphere (top right) and a wedge-shaped rock (bottom right).

Low-frequency SAS, as a complement to high-frequency SAS, offers the advantages of enhanced capabilities in sediment penetration and object classification. The differences in an object’s acoustic response and the ability of sound waves to penetrate the sediment differ significantly between high-frequency systems (>> 100 kHz) and low-frequency systems (<< 100 kHz) [14]. The use of low frequencies and the presence of a roughly textured seabed enable penetration into sandy substrates, so that such a system can detect objects in the top sediment layer–which would otherwise be opaque to higher frequency systems. An example is given in Fig. 3, where a flush-buried torpedo in Lübeck Bay found in 2016 appears significantly clearer in the SAS image recorded at 22 kHz (right) compared to the SAS image recorded at 75 kHz (left).

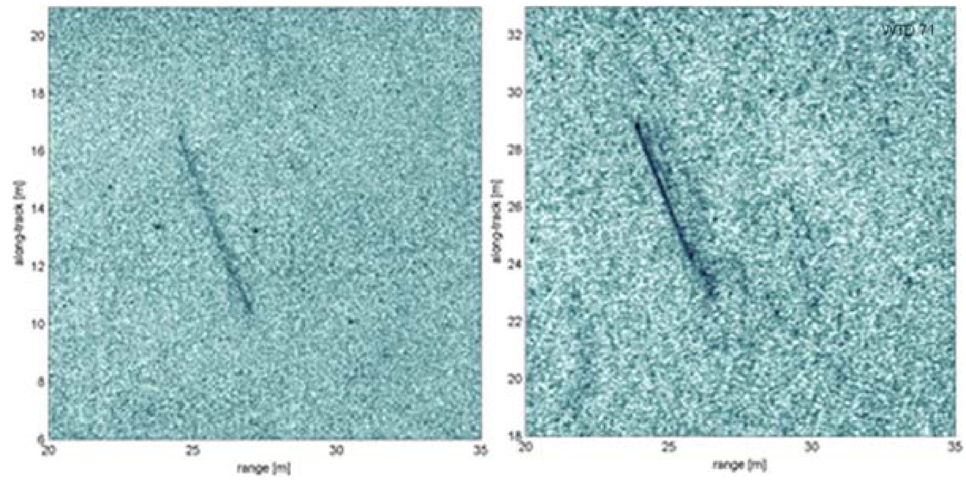

Fig.3: Images of flush-buried torpedo recorded with German SAS system at 22 kHz (right) and 75 kHz (left).

Low-frequency downward-looking SAS systems have been developed that create modest-range 3-D images of the sediment volume. One such example is the broadband Buried Object Scanning Sonar (BOSS) which traditionally has operated with acoustic wavelengths in the vicinity of 10 cm, and is capable of mapping voxels to similar dimensions. Over the last 15 years, work has been done in merging this system on an AUV with a magnetic gradiometer and optical sensor for classification of buried munitions [15]. An example is shown in Fig. 4, where the magnetic gradiometer provides a magnetic moment and localization (yellow dot on other images) illustrated by the 3-axis gradiometer time series, and the BOSS processing software creates top-, front-, and side-view maximum intensity projections of the sediment volume. The optical sensor does not reveal any surface expression because the object is fully buried. Thus, by combining shape from imagery with magnetic characteristics, high confidence classification of buried munitions is possible. Exploitation of frequency diversity for this and a variety of other sonars (or combinations of systems) may also improve UXO classification via analysis of target strength as a function of acoustic wavelength and other spatial/temporal parameters [7,16-18]. This represents an active research area as discussed in Ref. 5. It is expected that these types of downward-looking low-frequency sonar systems combined with magnetic or EMI sensors will play a key role in the mapping of UXO that are buried, which may account for more than 70% of munitions contamination [19].

Other active areas of research in UXO mapping sensors include automatic target recognition and multi-sensor fusion [4,8,9,14,15,20], active-source optics [4] and parametric sonar development [4,5,9].

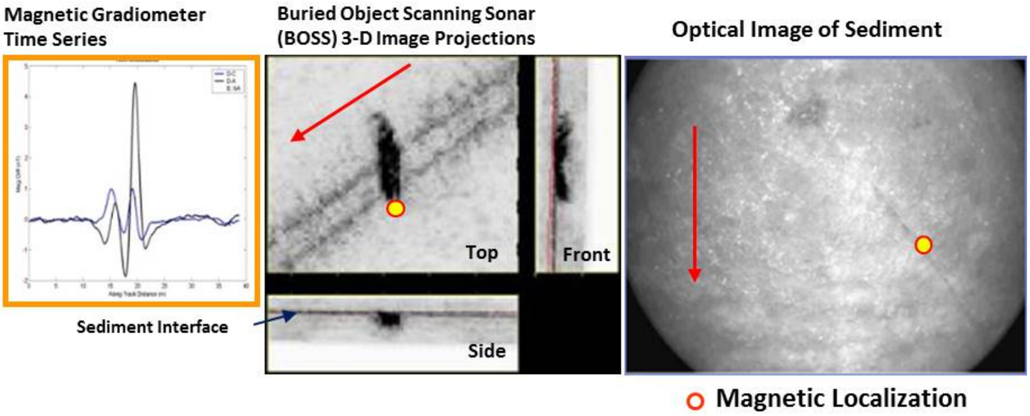

Fig.4: Gradiometer time series, BOSS and optical imagery of buried cylinder.

3. INTERNATIONAL COLLABORATION

Given the scope of the munitions contamination problem, it is not surprising that significant international collaboration in munitions response has grown over the decade. Defense research establishments from European countries adjacent to the Celtic, North and Baltic Seas have been discussing and sharing data, which include: Germany, United Kingdom, Netherlands, Belgium, France and Norway. In 2013, the U.S. Office of Naval Research and the Strategic Environmental Research & Development Program office hosted a workshop on Acoustic Detection and Classification of Unexploded Ordnance in the Underwater Environment, which saw participation from 6 countries [5].

2015 saw the beginning of a U.S. Department of Defense Coalition Warfare Program between the Naval Surface Warfare Center, Panama City Division from the United States and the Bundeswehr Technical Center for Ships and Naval Weapons, Maritime Technology and Research (WTD71) from Germany, in partnering to enhance joint capabilities in mapping underwater munitions in challenging and harsh environments–with an emphasis on utilizing unmanned underwater vehicles for detection and localization of buried objects. This program conducted its first joint munitions survey in September 2016 [9] in the Baltic Sea over various known and suspected UXO dumping sites dating back to WWII, with a second joint survey planned for late 2017.

4. DISCUSSION & FUTURE DIRECTION

This paper reviews the conventional underwater sensing technologies that have been used for the mapping of underwater unexploded ordnance, and describes emerging advances in underwater sensors, platforms, and automation predicted to increase the efficiency of munitions classification in many areas and make munitions detection and classification possible for the first time in buried, cluttered and other challenging environments. These include: high-frequency and low-frequency synthetic aperture sonar; advances in magnetometers, magnetic gradiometry, and electro-magnetic induction; advances in signal and information processing; and the development of autonomous undersea vehicles and sophisticated tow platforms. These advances are being evaluated and realized at an accelerated pace due to a number of international collaborations in munitions mapping and remediation.

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